AFRL-RQ-WP-TP 2017-0090

PERFORMANCE COMPARISON OF FINEMET AND METGLAS TAPE CORES UNDER NON-SINUSOIDAL WAVEFORMS WITH DC BIAS (POSTPRINT)

Zafer Turgu and James Scofield
Power and Control Division: Electrical Systems Branch

Hiroyuki Kosai and Tyler Bixel Hiroyuki Kosai and Tyler Bixel
UES Inc.

JUNE 2017

DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.

See additional restrictions described on inside pages

AIR FORCE RESEARCH LABORATORY
AEROSPACE SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7541
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the USAF 88th Air Base Wing (88 ABW) Public Affairs Office (PAO) and is available to the general public, including foreign nationals.

Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RQ-WP-TP-2017-0090 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

X

JOSEPH N. MERRETT
Project Manager
Electrical Systems Branch
Power and Control Division

X

GREGORY L. FRONISTA, Chief
Electrical Systems Branch
Power and Control Division

This report is published in the interest of scientific and technical information exchange and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2017	Journal Article Postprint	01 October 2015 – 01 June 2017

4. TITLE AND SUBTITLE
PERFORMANCE COMPARISON OF FINEMET AND METGLAS TAPE CORES UNDER NON-SINUSOIDAL WAVEFORMS WITH DC BIAS (POSTPRINT)

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

6. AUTHOR(S)
Zafer Turgu and James Scofield (Power and Control Division: Electrical Systems Branch)
Hiroyuki Kosai and Tyler Bixel (UES Inc.)

5d. PROJECT NUMBER
3145

5e. TASK NUMBER

5f. WORK UNIT NUMBER
EXAMPLE: Q1N8

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Power and Control Division
Electrical Systems Branch
Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433-7542

UES Inc.
4401 Dayton Xenia Rd
Beavercreek, OH 45432

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RQ-WP-TP-2017-0090

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQQE

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TP-2017-0090

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES
This article was published in the IEEE Transactions on Magnetics, Vol 52, Issue 7, July 2016. © 2016 IEEE. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT
In a previous paper, we introduced a modified Steinmetz equation to account for dc-bias field effects, which requires only a simple dc permeability measurement to predict total power loss. In this paper, we expanded our investigation to include Finemet nanocrystalline material and found that our modified Steinmetz formalism was effective in predicting dc-bias-related losses for this system as well. In this paper, it was observed that Finemet cores exhibit lower losses than Metglas cores under identical test frequencies and bias fields. In addition, we show that a full characterization of the dc loss component necessitates the consideration of higher order ($n > 1$) harmonic components. In order to quantify these higher frequency loss components, a dc–dc converter-based test system was built to intentionally introduce inductor current harmonics by varying the filter capacitance and parasitic inductance of the test system. Both core types were evaluated under fundamental frequencies of 20 to 150 kHz and dc-bias fields of up to 1.3 kA/m, with the inclusion of distorted waveforms obtained by varying filter capacitance. At higher frequencies, the Metglas cores were found to exhibit greater loss fractions associated with the higher order harmonic components. A detailed summary of the measured core loss characteristics for both core types is included and discussed. This paper includes the details of the measurements, the modified Steinmetz relation, and the loss extraction algorithm used for analysis.

15. SUBJECT TERMS
electronic reliability, high temperature, power distribution and conversion, power electronics, silicon carbide

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Joseph N. Merrett
Unclassified	Unclassified	Unclassified	SAR	7	**19b. TELEPHONE NUMBER** (Include Area Code) N/A

Performance Comparison of Finemet and Metglas Tape Cores Under Non-Sinusoidal Waveforms With DC Bias

Hiroyuki Kosai[1,2], Zafer Turgut[1], Tyler Bixel[1,2], and James Scofield[1]

[1]Air Force Research Laboratory, Wright Patterson AFB, OH 45433 USA
[2]UES Inc., Beavercreek, OH 45432 USA

In a previous paper, we introduced a modified Steinmetz equation to account for dc-bias field effects, which requires only a simple dc permeability measurement to predict total power loss. In this paper, we expanded our investigation to include Finemet nanocrystalline material and found that our modified Steinmetz formalism was effective in predicting dc-bias-related losses for this system as well. In this paper, it was observed that Finemet cores exhibit lower losses than Metglas cores under identical test frequencies and bias fields. In addition, we show that a full characterization of the dc loss component necessitates the consideration of higher order (n > 1) harmonic components. In order to quantify these higher frequency loss components, a dc–dc converter-based test system was built to intentionally introduce inductor current harmonics by varying the filter capacitance and parasitic inductance of the test system. Both core types were evaluated under fundamental frequencies of 20 to 150 kHz and dc-bias fields of up to 1.3 kA/m, with the inclusion of distorted waveforms obtained by varying filter capacitance. At higher frequencies, the Metglas cores were found to exhibit greater loss fractions associated with the higher order harmonic components. A detailed summary of the measured core loss characteristics for both core types is included and discussed. This paper includes the details of the measurements, the modified Steinmetz relation, and the loss extraction algorithm used for analysis.

***Index Terms*— Core loss, DC–DC converter, inductor, soft magnetic materials.**

I. Introduction

OWING to their design requirements or unintentional interference, soft-magnetic components in electronic systems are often subjected to dc-bias-flux conditions. Inductive elements in switch-mode power supplies and core steel sheets in permanent magnet machines are representative of components operating under the dc-bias-flux conditions. These dc-bias conditions result in distorted hysteresis loops and significantly increased core losses and have been shown to be relatively independent of core material. The physical origin of these increased losses is not well understood. Higher local coercivity and increased hysteresis [1]–[3] and magnetomechanical damping and/or magnetostriction [4], [5] have been proposed as mechanisms for increased losses under dc-bias conditions. Classical theory separating core loss into hysteresis, eddy current, and anomalous components has been insufficient to describe these losses, as have classical Steinmetz predictions [6]. These theoretical deficiencies, coupled with the complete lack of dc loss attributes on core manufacturer's data sheets, result in a requirement to empirically determine loss values for specific design applications. These deficiencies have motivated us to extend our investigation into dc-bias losses in tape core inductors operating in a dc–dc boost converter.

In a previous paper [7], we introduced a modified Steinmetz equation that accounts for dc-bias core effects and takes advantage of a simple dc permeability measurement to predict total power loss. This formalism was based on measurements performed on a Fe-based Metglas tape core using non-sinusoidal waveforms. In this paper, we expanded our investigation to include Finemet core materials and found that the modified Steinmetz formalism was effective in predicting dc-bias related losses in this system as well. The evaluation of the modified Steinmetz formalism on the alternative material system yielded a one by one comparison of identically sized Metglas and Finemet tape cores. These cores were used to fabricate boost inductors for a dc–dc converter setup used as the test-bed to assess loss characteristics under varying dc-bias fields. The only difference between these epoxy impregnated cores was their stacking density; the Metglas cores were comprised of $\sim$25 μm-thick tapes and had a manufacturer-specified stacking density of 85%–90%, while the Finemet cores were made from $\sim$17 μm-thick tapes with an estimated stacking density of 78%–84%. Since the cross-sectional areas for both cores were sufficient to mitigate saturation, stacking density differences should have had no effect on the obtained results.

In addition to identifying the dc-bias related losses, this paper also identified the non-negligible contribution to core losses from higher order (n > 1) harmonic components. In order to quantify these higher frequency loss components, the dc–dc converter-based test system was modified to intentionally introduce inductor current harmonics by varying the filter capacitance and the parasitic inductance. Loss behaviors of the two cores under these dynamic switching conditions are a significant aspect of this paper.

II. Experiment

A. Experimental Setup

The modified Air Force Research Laboratory inductor test system is modular by design and configurable as a dc–dc boost converter similar to that described in [7]. The single-phase half-bridge module includes a removable 30 μF X7R filter capacitor across the upper and lower switches, which may be removed to exacerbate the high-frequency switching dynamics in the inductor. A dual-channel Agilent 33500B waveform generator provides frequency and duty cycle controls for boost-converter operation. Input power was supplied to the test station from two Agilent 6030 A dc power supplies connected in parallel. The test inductor's secondary voltage and primary

Manuscript received November 5, 2015; revised December 16, 2015; accepted December 21, 2015. Date of publication January 22, 2016; date of current version June 22, 2016. Corresponding author: H. Kosai (e-mail: hiroyuki.kosai@wpafb.af.mil).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2015.2512438

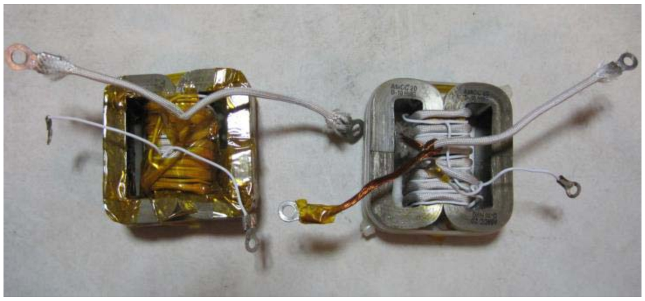

Fig. 1. Finemet inductor (left) and Metglas inductor (right).

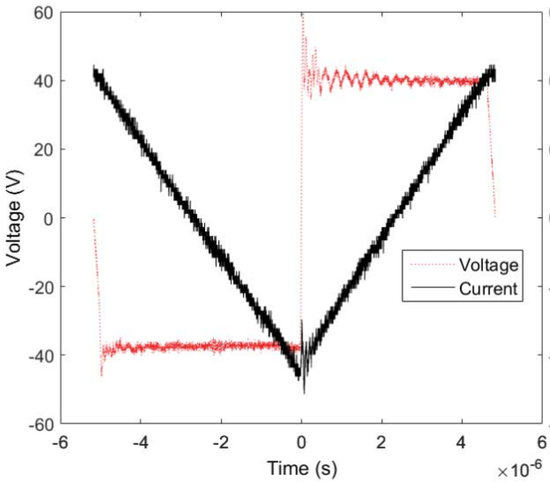

Fig. 2. DC–DC converter secondary-winding voltage and primary-winding ac current profiles. (Metglas 100 kHz, 40 V, 40 Ω with a filter capacitor.)

current were measured by a LeCroy WaveRunner 104MXi and analyzed using our modified Steinmetz formalism. Relative delays due to probe characteristics as well as the experimental setup were analyzed and calibrated [7].

Identically sized inductors, fabricated using the Metglas (Hitachi AMCC20) and Finemet (MK Magnetics SC2049M1) cores, were selected for investigation and are shown in Fig. 1. The tested inductors were configured with nine primary- and nine secondary-winding turns providing self-inductance values of 365 and 298 μH for the Metglas and Finement cores, respectively. For each test, the secondary-winding voltage and the primary-winding current were measured to obtain the inductor's magnetic flux density and magnetic field intensity. A constant ΔB amplitude was maintained at $\sim$0.0336 T by varying the applied voltage at each test frequency (60 V–150 kHz, 40 V–100 kHz, 20 V–50 kHz, and 8 V–20 kHz).

B. DC–DC Converter Test Measurements With a Filter Capacitor

All measurements described in this section were taken with the AVX 300 V, 30 μF filter capacitor installed. Connection to a variable resistance load bank necessitated 1.5 m of cabling, and another AVX 300 V, 30 μF capacitor was directly installed inside the load bank to balance the parasitic line inductance.

Fig. 2 shows typical primary current and secondary voltage waveforms from the Metglas dc–dc converter inductor under test. Since these waveforms are not sinusoidal, higher harmonic modes in addition to the fundamental frequency are present. Therefore, Fourier analysis results in nonzero higher order harmonics inclusion. Fig. 3 shows typical ac current and voltage–frequency spectra obtained from the filtered data.

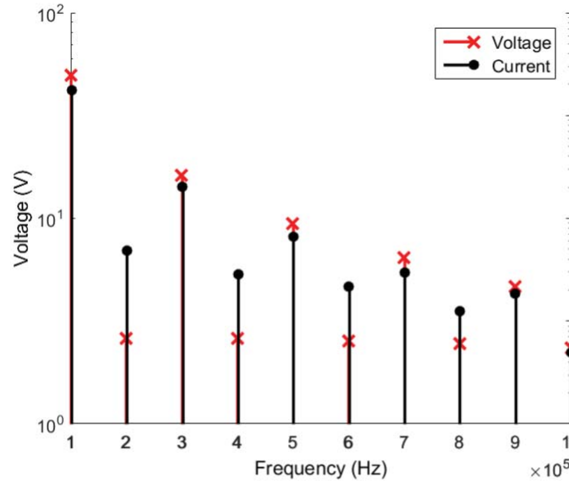

Fig. 3. Secondary-winding voltage and primary-winding ac current frequency spectra. DC current offset level was 3.89 A. (Metglas 100 kHz, 40 V, 40 Ω with a filter capacitor.)

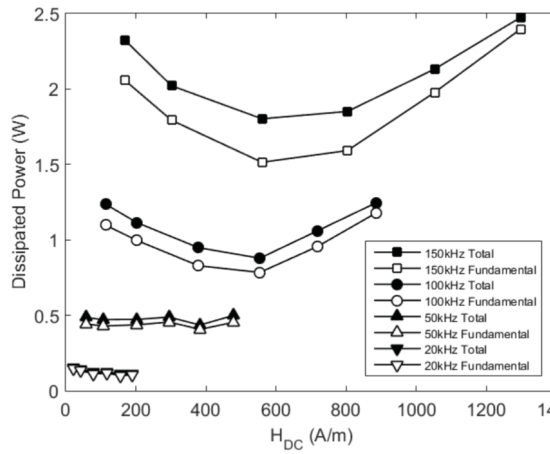

Fig. 4. Metglas core losses for various $H_{\rm dc}$ fields.

As a result, through power and reactive power have a similar spectral content. Figs. 4 and 5 show the total and fundamental-mode power losses as a function of $H_{\rm dc}$ for the Metglas and Finemet inductors. The fundamental mode contained an average 90.9% of the Metglas core loss and 88.3% of the Finemet's inductor loss.

As shown in Fig. 5, Finemet inductor core losses increase dramatically above 800 A/m, whereas the Metglas inductor did not exhibit this behavior. This sudden increase of power loss is most likely due to operation near the core saturation region. For the Finemet inductor, the corresponding B fields for 800, 1043, and 1284 A/m $H_{\rm dc}$ values were 0.97, 1.007, and 1.025 T, respectively. These B fields are very close to the Finemet saturation field of $\sim$1.23 T. However, for the Metglas inductor, the corresponding B field at 1280 A/m was 1.134 T, where the saturation field of the core is 1.56 T. For $H_{\rm dc}$ values below 800 A/m, Finemet core losses were found to be consistently lower ($\sim$27.7%) than the corresponding Metglas power losses.

In our recent work [8], we studied hysteresis losses of tape, ferrite, and dust core inductors under dc-bias conditions.

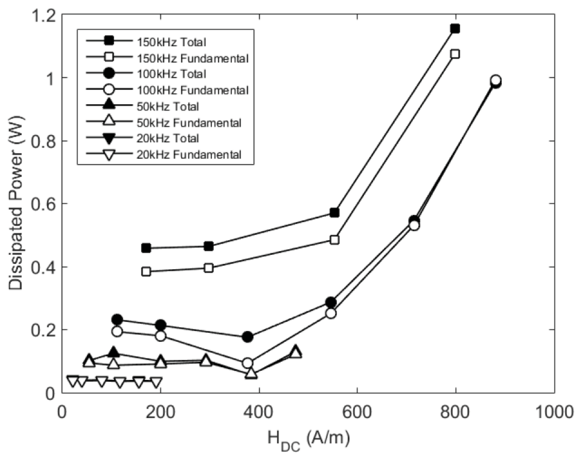

Fig. 5. Finemet core losses for various H_{dc} fields.

TABLE I

SUMMARY OF STEINMETZ FREQUENCY COEFFICIENT α AND B FIELD COEFFICIENT β FOR METGLAS AND FINEMET

Core material	Metglas	Finemet
Frequency coefficient α	1.3113	1.1146
B field coefficient β	2.0349	2.0861

We concluded that the loss curve shape of Fig. 4 is driven by hysteresis loss. In addition, power loss minima on the higher frequency curves correspond to H_{dc} values associated with a permeability maximum ($\mu_{\max}$) typical of μ versus H_{dc} static measurements. The Finemet curves of Fig. 5 do not reflect this behavior, since $\mu_{\max}$ occurs at low H_{dc} values, which fall below that of our data revealing only the increasing portion of the curves. Our modified Steinmetz formalism is valid only for the higher bias-field part of the loss curves in Fig. 4, where $H(\mu) > H(\mu_{\max})$.

It should be noted that the slight depression in the dissipated power of the 50 and 100 kHz Finemet curves of Fig. 5 is due to reduced current probe sensitivity resulting from the measurement system range transition from 200 to 1 A/div at just below 400 A/m, in response to the increasing primary-winding dc current. Thus, these depressions are associated with systematic measurement artifacts and not by the Finemet inductor μ versus H_{dc} properties.

Operating frequencies of 20–150 kHz and applied voltages of 20–60 V were used to find the classical Steinmetz frequency coefficient α, B field coefficient β, and constant k for the Steinmetz equation ($P = kf^{\alpha}B^{\beta}$). In determination of α, β, and k, we employed the lowest possible bias-current settings, since the experimental setup cannot be operated without a bias current. Presence of the bias does not affect α and β values but the estimated k parameter changes due to the offset introduced by the bias field. Due to this introduced error in k, it was renamed as parameter A and treated as a variable while fitting (2) to the experimental data. Since these measured voltage and current waveforms were non-sinusoidal, the resultant coefficients were different from the values claimed by the core manufactures. The units of power loss density P and coefficient k are in W/kg, frequency f is in kHz, and field B is in tesla. Table I summarizes those parameter fits.

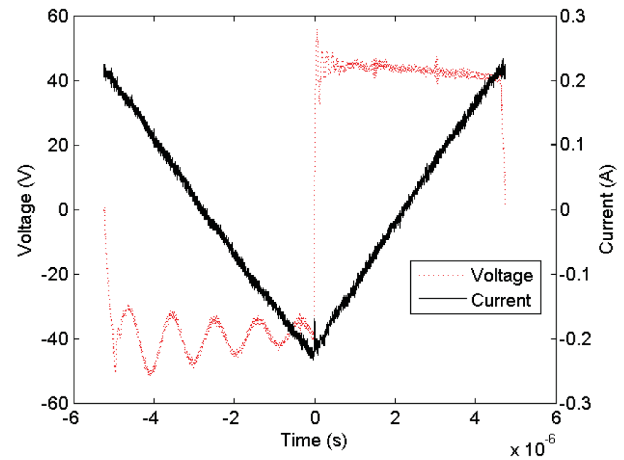

Fig. 6. Voltage and ac current waveforms for the same condition as in Fig. 4. (Metglas 100 kHz, 40 V, 40 Ω without filter cap.)

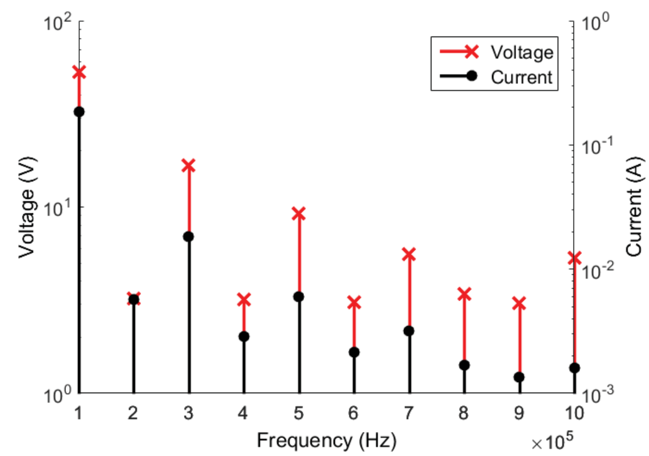

Fig. 7. Secondary-winding voltage and primary-winding ac current frequency spectra. DC current offset level was 3.92 A. (Metglas 100 kHz, 40 V, 40 Ω without a filter capacitor.)

C. DC–DC Converter Test Measurements Without a Filter Capacitor

To investigate the influence of higher order harmonic spectra on core losses, we intentionally removed the power board's filter capacitor to increase the amplitude of these components. These spectral or noise components of converter voltage and current waveforms originate from the non-sinusoidal, switched nature of circuit operation and are thus present in all topologies. Fig. 6 shows the inductor waveforms without the output filter capacitor, and the increased noise in the signal and a corresponding frequency spectra plot in Fig. 7. Power losses in the inductor for 100 kHz converter operation are compared in Fig. 8 for filtered and unfiltered operation. Fig. 8 clearly shows that increasing the harmonic spectral content measurably increases core losses. Highlighted by the arrows in Fig. 8, the unfiltered data reflects reduced H_{dc} values at higher bias-field operation. This is due to increased losses in other circuit elements at a fixed output load resistance setting.

Table II shows apparent and loss power for Finemet inductors as a function of mode number with and without output filtering. Although the fundamental mode contains a majority of the power, apparent, or loss, the ratio of fundamental mode to total loss for the Metglas and Finemet cores were reduced to 77.6% and 79.0%, respectively, on average across the four fundamental frequencies tested. Comparing these

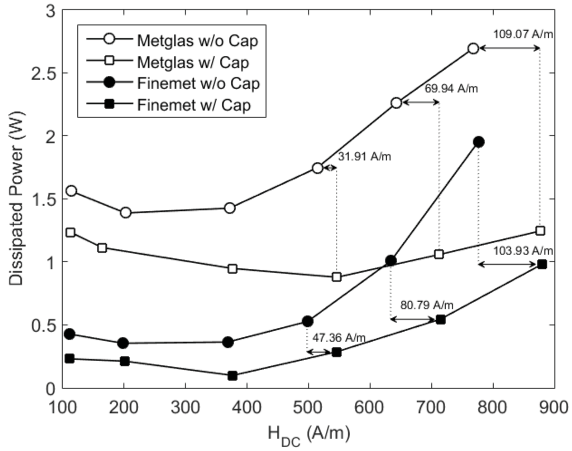

Fig. 8. Metglas and Finemet inductor power loss comparison between with and without the filter capacitor under 100 kHz operations.

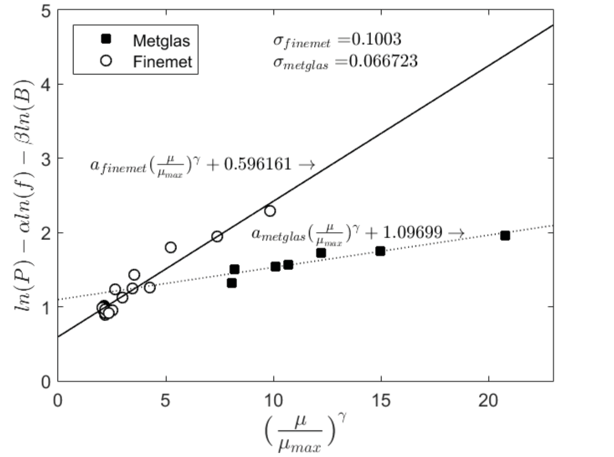

Fig. 9. Left terms of (2) and their best fit lines were plotted as a function of $[\mu/\mu_{\max}]^\gamma$ for the Metglas and Finemet inductors.

TABLE II

APPARENT AND LOSS POWER FOR FINEMET INDUCTORS AT 100 kHz

	Harmonic	n=1	n=2	n=3	n=4	n=5	Total
Apparent Power (W)	With Capacitor	4.375	0.006	0.163	0.004	0.031	4.617
	Without Capacitor	4.85	0.009	0.151	0.005	0.028	5.078
Power Loss (W)	With Capacitor	0.18	0	0.015	0.001	0.004	0.213
	Without Capacitor	0.318	0	0.019	0	0.007	0.355

results with the filtered signal data, it is apparent that the filter capacitor reduces both $n > 1$ harmonic and total power losses.

III. EXPERIMENTAL ANALYSIS

Data representative of Figs. 4 and 5, in which power loss was measured as a function of $H_{\rm dc}$, was evaluated using our modified Steinmetz equation [7] shown in

$$P = \frac{A}{\exp(a)} f^\alpha B^\beta \exp\left[a\left(\frac{\mu}{\mu_{\max}}\right)^\gamma\right] \tag{1}$$

where μ, $\mu_{\max}$, a, A, and γ are the permeability under non-zero bias condition, maximum dc permeability, coefficient, power density coefficient, and exponential parameters, respectively. In order to assess the validity of the proposed modified Steinmetz relation, all of the filtered experimental Finemet and Metglas results above 550 A/m $H_{\rm dc}$ were evaluated. Using the α and β coefficients from Table I and rewriting (1) as the linear relationship shown in (2), best fit lines to the data were plotted as a function of $[\mu/\mu_{\max}]^\gamma$

$$Ln(P) - \alpha Ln(f) - \beta Ln(B) = Ln\left(\frac{A}{\exp(a)}\right) + a\left[\frac{\mu}{\mu_{\max}}\right]^\gamma. \tag{2}$$

In this analysis, as in our previous works, the case ($\gamma = -1$) was chosen, since this selection of γ value yielded best fit results. Using the measured values of μ, $\mu_{\max}$, α, and β for Finemet and Metglas, the parameters A, and a were estimated by curve fitting of the experimental data (Fig. 9) and are shown in Table III. It should be noted that the values for A, which were measured above $H(\mu_{\max})$, were not identical to the k parameters, which were measured below $H(\mu_{\max})$. From this analysis, it is clearly shown that the experimental data are successfully fit using the modified Steinmetz relationship.

TABLE III

FINEMET AND METGLAS COEFFICIENTS

	Metglas	Finemet
$\mu_{\max}$	3013	2452.6
a	0.0434	0.1826
A (W/kg)	3.128	2.179

IV. CONCLUSION

DC-bias dependent loss phenomenon in identically sized Fe-based Metglas and Finemet core inductors was investigated using a dc–dc boost converter. For all experiments, ΔB was maintained constant while $H_{\rm dc}$ was varied by changing the converter's load resistance. Finemet power losses were found to be substantially lower than Metglas losses when operated under identical conditions. For both the core materials, the results show that core losses increase with bias field ($H_{\rm dc}$), and a proposed empirical relationship was utilized to provide a good fit to experimental loss data. It was also shown that high-frequency components have a non-negligible effect on core losses. Associated standard deviation between the measured results and the best fit lines are shown in Fig. 9.

REFERENCES

[1] C. A. Baguley, U. K. Madawala, and B. Carsten, "A new technique for measuring ferrite core loss under dc bias conditions," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 4127–4130, Nov. 2008.

[2] V. C. Valchev, A. P. Van den Bossche, and D. M. Van de Sype, "Ferrite losses of cores with square wave voltage and DC bias," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2005, pp. 837–841.

[3] P. M. Gradzki and F. C. Lee, "Domain wall resonance and its effect on losses in ferrites," in *Proc. Annu. IEEE Power Electron. Specialists Conf.*, Jun. 1991, pp. 627–632.

[4] V. J. Thottuvelil, T. G. Wilson, and H. A. Owen, "Unusual high-frequency behavior of some amorphous metallic-alloy tape-wound magnetic cores," *IEEE Trans. Magn.*, vol. 20, no. 4, pp. 570–578, Jul. 1984.

[5] C. A. Baguley, U. K. Madawala, and B. Carsten, "Unusual effects measured under dc bias conditions on MnZn ferrite material," *IEEE Trans. Magn.*, vol. 45, no. 9, pp. 3215–3222, Sep. 2009.

[6] J. Muhlethaler, J. Biela, J. W. Kolar, and A. Ecklebe, "Core losses under DC bias condition based on Steinmetz parameters," in *Proc. Int. Power Electron. Conf.*, Jun. 2010, pp. 2430–2437.

[7] H. Kosai, Z. Turgut, and J. Scofield, "Experimental investigation of dc-bias related core losses in a boost inductor," *IEEE Trans. Magn.*, vol. 49, no. 7, pp. 4168–4171, Jul. 2013.

[8] Z. Turgut, H. Kosai, T. Bixel, J. Scofield, S. L. Semiatin, and J. Horwath, "Hysteresis loss analysis of soft magnetic materials under direct current bias conditions," *J. Appl. Phys.*, vol. 117, p. 17A508, May 2015.